

REPORT No. 469

INCREASING THE AIR CHARGE AND SCAVENGING THE CLEARANCE VOLUME OF A COMPRESSION-IGNITION ENGINE

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SUMMARY

The object of the investigation presented in this report was to determine the effects of increasing the air charge and scavenging the clearance volume of a 4-stroke-cycle compression-ignition engine having a vertical-disk form of combustion chamber.

Boosting the inlet-air pressure with normal valve timing increased the indicated engine power in proportion to the additional air inducted and resulted in smoother engine operation with less combustion shock.

Scavenging the clearance volume by using a valve overlap of 145° and an inlet-air boost pressure of approximately $2\frac{1}{2}$ inches of mercury produced a net increase in performance for clear exhaust operation of 33 percent over that obtained with normal valve timing and the same boost pressure. The engine tests indicate that, with a large valve overlap, $2\frac{1}{2}$ inches of mercury boost pressure is sufficient to scavenge completely the clearance volume, and that the increase in engine power effected by scavenging the clearance volume, for a constant fuel quantity, is more than twice what could be obtained from the additional air charge alone. The improved combustion characteristics result in lower specific fuel consumption, and a clearer exhaust. The starting and idling characteristics were not affected by variation in boost pressure or by the use of scavenging with a large valve overlap.

Analysis of the exhaust of several compression-ignition engines showed the carbon monoxide gas content to be less than one half of 1 percent when operating with a clear exhaust.

INTRODUCTION

The work of the National Advisory Committee for Aeronautics in developing the 4-stroke-cycle compression-ignition engine for aircraft use has been carried on chiefly with two different types of these engines. The one type utilizes high velocity of air flow to obtain the necessary mixing of the air and fuel in the combustion chamber, while the other type has no effective air flow at the time of the injection of the fuel and the fuel itself must be distributed as uniformly as possible to obtain the required mixture of air and fuel.

The latter type of engine with its quiescent combustion chamber has been used for a series of tests which led to the development of multiple-orifice nozzles and verified the proportional-area principle for the design of these nozzles as reported in references 1 and 2. After this work had been completed, attention was turned toward increasing the amount of air available for combustion as a means for increasing the power developed.

It has become accepted practice to increase the power output of the spark-ignition aircraft engine by boosting the inlet-air pressure so that the engine will induct more charge than would be inducted under atmospheric pressure. The work of Schey and Young (reference 3) with a spark-ignition engine has shown the additional increase in engine power that may be obtained by boosting when using a large valve overlap to effect better scavenging of the clearance volume. They have pointed out that the ratio of the power with complete scavenging to that with normal scavenging should be equal to the ratio of the volumes of the charge $r/(r-1)$ where r is the compression ratio. This formula shows that with an increase in compression ratio the increase in power to be obtained decreases; therefore, it does not seem to offer much advantage for the compression-ignition engine on a comparative basis with the spark-ignition engine. However, boosting the air charge in a compression-ignition engine showed better net fuel economy and caused the engine to operate with less combustion shock (reference 4).

Boosting a 4-stroke compression-ignition engine not only introduces more air per cycle for supporting combustion, but it also reduces the proportional amount of residual gases in the air charge, because the amount of residual gases carried over is practically constant depending upon the exhaust back pressure. As the amount of residual gases left in the combustion chamber is affected by a change of valve timing, the engine performance was investigated both with normal valve timing and boosting and also with a large valve overlap and boost pressures to effect better scavenging of the clearance volume.

This investigation was conducted during 1931 and 1932 in the power plants laboratory of the National Advisory Committee for Aeronautics at Langley Field, Va.

APPARATUS AND METHODS

The engine and combustion chamber used in these tests are described in references 1 and 2. The combustion chamber (fig. 1) is a vertical disk-shaped space formed between the valve heads and has a smooth, flared orifice connecting this space to the main cylinder. The piston runs within mechanical clearance of the cylinder head, insuring the displacement of the air charge into the combustion chamber. For all the test data presented in this report the compression ratio was held constant at 12.6. Unless engine speed

from the individual orifices in a container with a long neck shown in figure 2. The sum of the weights of the sprays from the individual orifices caught in this way was within ± 1 percent of the weight of the sprays from all orifices caught simultaneously under the same conditions. The areas of the orifices discharging insufficient fuel were increased until all spray discharges were in the proper ratio. The nozzle as finally used had two main orifices of 0.020-inch diameter, two intermediate orifices of 0.011-inch diameter, and two outside orifices of 0.007-inch diameter. The orifices were arranged symmetrically about the center line of the nozzle with an angle of 25° between adjacent axes.

With the injection system used for these tests the duration of injection for a fuel quantity of 0.000325 pound per cycle was 24 crank degrees at 1,500 engine

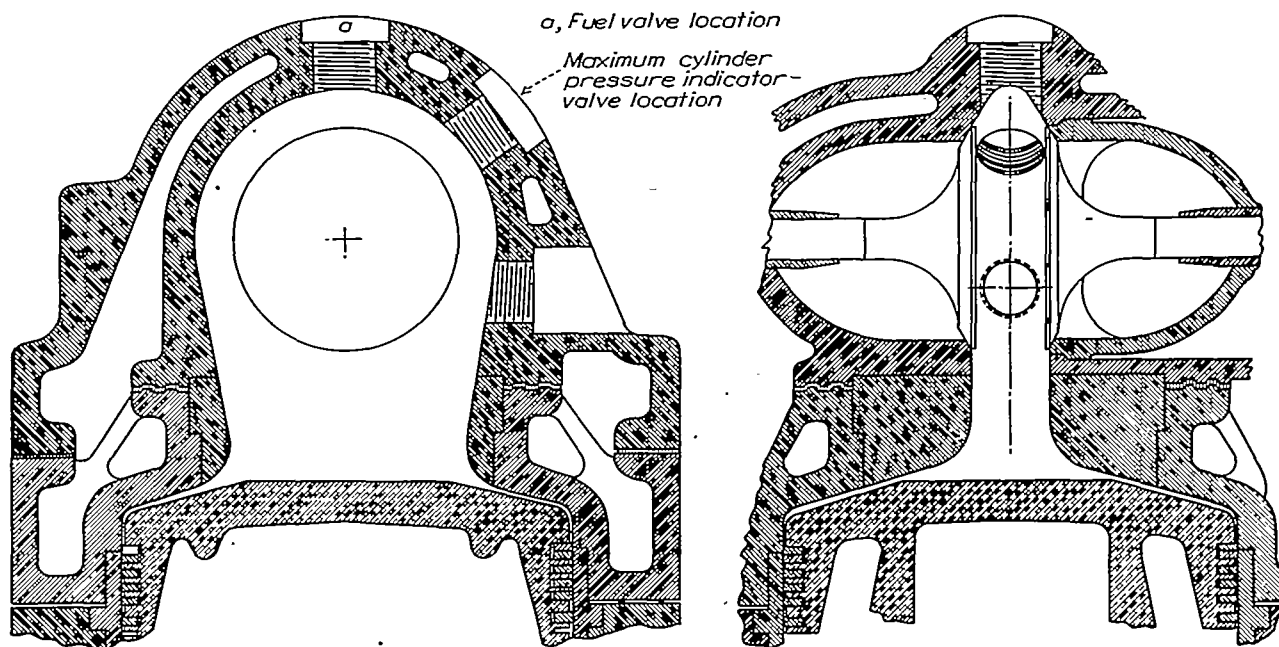


FIGURE 1.—Combustion chamber.

was the variable the speed was held constant at 1,500 r.p.m.

The fuel pump used for the tests was a cam-operated plunger pump with a poppet by-pass control. A spring-loaded automatic injection valve, set to open at 3,000 pounds per square inch, was installed in the top hole of the combustion chamber. The fuel-injection valve nozzle used had six round-hole orifices arranged in a plane parallel to the heads of the exhaust and inlet valves.

Observation of the fuel spray in the atmosphere indicated that, as the areas of the orifices were increased for the greater discharge area required for boosted operation, the flow of fuel from the large main orifices reduced the effective pressure on the other orifices and therefore the fuel distribution did not fulfill the requirements outlined in reference 2. This lack of proportion was verified by catching sprays

r.p.m. The fuels used were conventional Diesel-engine fuels described in reference 5 as fuels no. 1 and no. 2. The injection advance angle was determined by noting, with the aid of a Stroborama, the start of fuel spray while injecting into the atmosphere.

Figure 3 shows a flow-area diagram both for the normal valve timing and for the valve-overlap timing used for the engine tests. The ordinate represents the area exposed to gas flow at the inner valve seat diameters. For the valve-overlap setting the valve heads were allowed to run within 0.016 inch of each other at the point of closest travel. This condition allowed as nearly as practicable a free path for the scavenging air through the combustion chamber.

Figure 4 is a schematic diagram of the apparatus used in conducting the tests. A Roots-type blower was separately driven at the required speeds for supplying air at pressures up to 10 inches of mercury. A 16-

cubic-foot tank was connected in the air duct between the blower and the engine for damping pulsations. A mercury manometer was installed on the tank for measuring the effective air-charging pressure. The

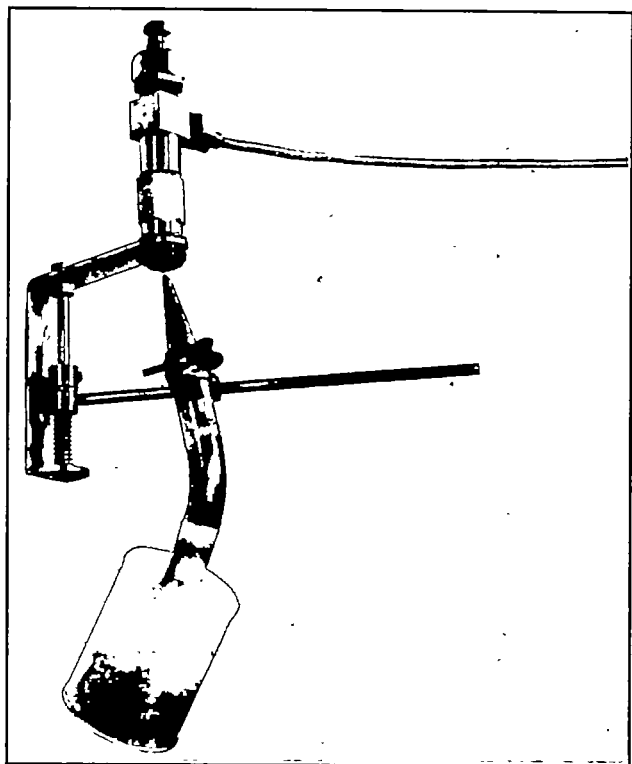


FIGURE 2.—Apparatus for catching sprays from individual orifices of a multiorifice nozzle.

length of the air duct between the tank and the engine was reduced to 15 inches to minimize the induction-wave effect. A revolution counter operated through an electro-magnetic clutch was used to record the blower

in boost pressure, but the variation for comparative tests was negligible.

Gas samples were taken at a point approximately 5 inches from the exhaust-valve port under conditions

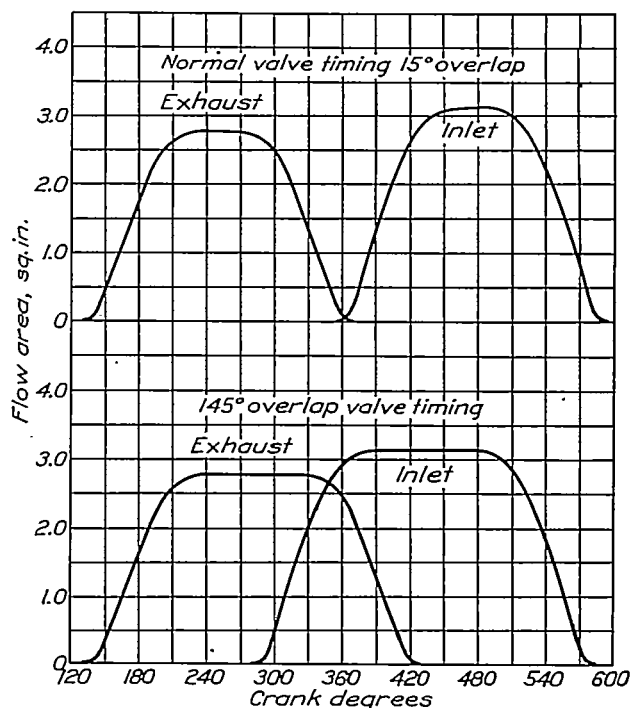


FIGURE 3.—Comparison of valve time-area diagrams with overlaps of 15° and 145°.

of variable-fuel quantity, with and without valve overlap and with and without boost pressure. A steel tube was used for conducting the gases to a sampling bottle. A modified Orsat gas-analysis apparatus

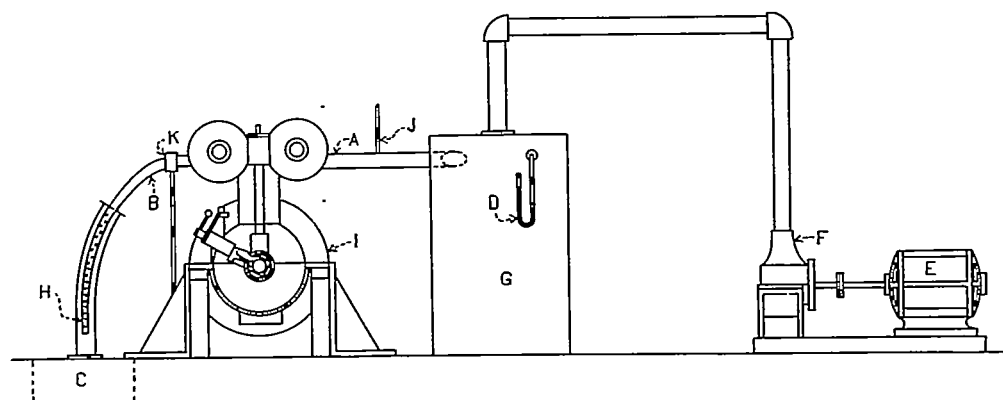


FIGURE 4.—Diagrammatic representation of air system.

A, Air duct 5" diameter, 15" long. *B*, Exhaust stack, 5' long: 3" diameter section, 2' 8"; Section 2' 4" tapers to 1 3/4" diameter. *C*, Exhaust trench. *D*, Manometer. *E*, Motor. *F*, Roots-type blower. *G*, Surge tank, 16 cu. ft. capacity. *H*, Tapered section, perforated. *I*, Test engine. *J*, Thermometer. *K*, Water sprayer.

revolutions during a test run. Slip-speed data taken over a range of speeds enabled calculations to be made for determining the air quantities delivered to the engine. The air temperature and barometric pressure were used for determining air weights. The air temperatures were not controllable and the temperature increased approximately 40° F. for a maximum increase

(reference 6) was used for analyzing the samples of exhaust gas.

For all conditions of engine operation the injection advance angle was increased until a light permissible knock was heard or until the maximum cylinder pressure reached 900 pounds per square inch as recorded by a modified Farnboro indicator. The limit of al-

lowable injection advance angle as judged from the sound of the engine was usually about 2° or 3° greater than the earliest advance angle at which no knock could be heard.

The exhaust gases were observed during the engine tests through a peephole located in the exhaust manifold about 11 inches from the exhaust-valve port. The limit of the clear-exhaust range, as used in the discussion, was that marked by the first appearance of short flashes of flame or of a slight haze.

The maximum cylinder pressures were obtained from the readings of a trapped-pressure indicator and

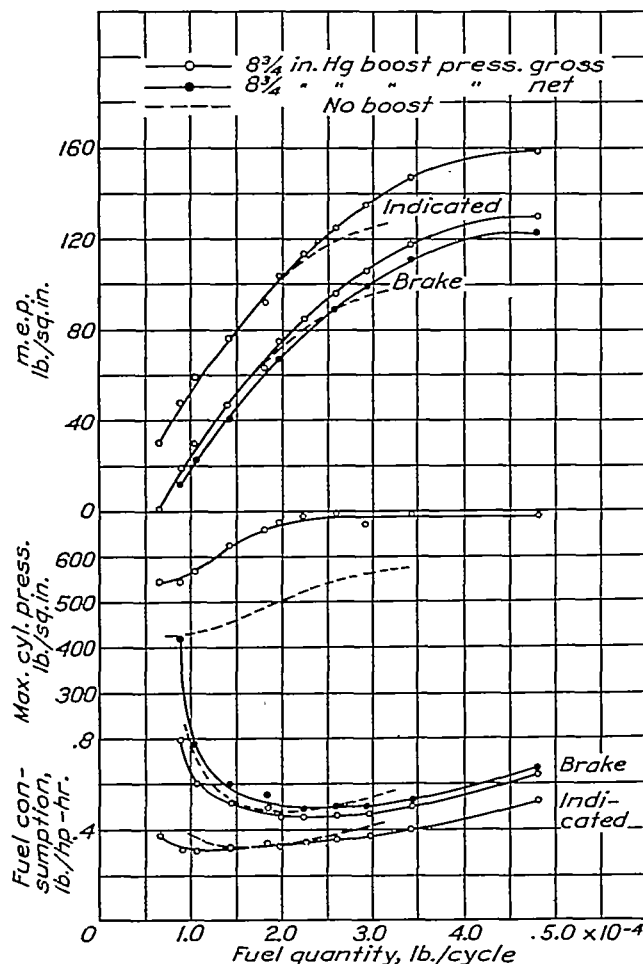


FIGURE 5.—Performance obtained with and without boost pressure (normal valve timing, speed 1,500 r.p.m.).

checked at intervals by a modified Farnboro indicator. The trapped-pressure readings are 10 to 70 pounds per square inch lower than the Farnboro readings.

All performance data shown in this paper are presented on a net basis by subtracting the power required by the blower. Unless otherwise stated, all comparative data were obtained under comparable engine operating conditions.

RESULTS AND DISCUSSION

Because of the accessory equipment driven by this single-cylinder test unit, the mechanical efficiency is

less than that obtained by a multicylinder engine. The mechanical efficiency of this engine calculated for full-load operation with no excess air is as follows: 77.0 percent for no boost and no valve overlap, 77.6 percent net for $8\frac{3}{4}$ inches of mercury boost and no valve overlap, 78.6 percent for no boost and with valve overlap, and 82.0 percent for $6\frac{1}{4}$ inches of mercury boost and with valve overlap.

Figure 5 shows the effect of boosting a compression-ignition engine with normal valve timing. The curves show that the gross brake mean effective pressure when boosting is equal to the unboosted value for the small fuel quantities. The net brake mean effective pressure, when boosting, is less than when unboosted for small fuel quantities but greater for all fuel quantities above 0.00025 pound per cycle. This fuel quantity corresponds to an excess air quantity of 30 percent for the normal engine. It has been found from the results of many tests that additional air increases the brake performance of the normal engine only when the engine is operated over a range of excess air from 0 to 30 percent. Excess fuel does not improve engine performance but may decrease the rate-of-pressure rise. It would appear from the data for indicated mean effective pressure that boosting an engine using normal valve timing increases the capacity of the engine and that the increase in indicated engine power is proportional to the additional amount of air inducted for a condition of approximately full-load operation. The balanced-diaphragm maximum-cylinder-pressure indicator shows that the difference in maximum cylinder pressure between individual cycles becomes considerably less when the engine is boosted. The engine operation becomes smoother with less combustion shock for boosted conditions. Although these results were obtained from tests at a compression ratio of 12.6, they should be true for other compression ratios except where other factors may have a greater influence on the engine operation. When boosting the air charge of a normally timed engine the proportional amount of residual gases in the fresh charge decreases and, as will be discussed later, these gases have an effect on the combustion characteristics.

Figure 6 shows the increase in engine performance with clear exhaust obtained by scavenging the combustion chamber. At zero boost pressure there is an increase in brake mean effective pressure and a decrease in fuel consumption when scavenging, even though the weight of air received by the engine is less than when using normal valve timing. This increase in brake mean effective pressure shows that the combustion characteristics are improved by the removal of the residual gases. The clear-exhaust performance for the large valve overlap increases very rapidly up to $2\frac{1}{4}$ inches of mercury boost pressure and then increases very slowly for further boost pressure. Thus it may be concluded that at $2\frac{1}{4}$ inches of mercury boost pressure the combustion chamber is

practically completely scavenged of residual gases and any further increase in performance is due to the additional air that can be trapped in the cylinder as the induction pressure is increased. The recorded compression pressures for scavenging operation show

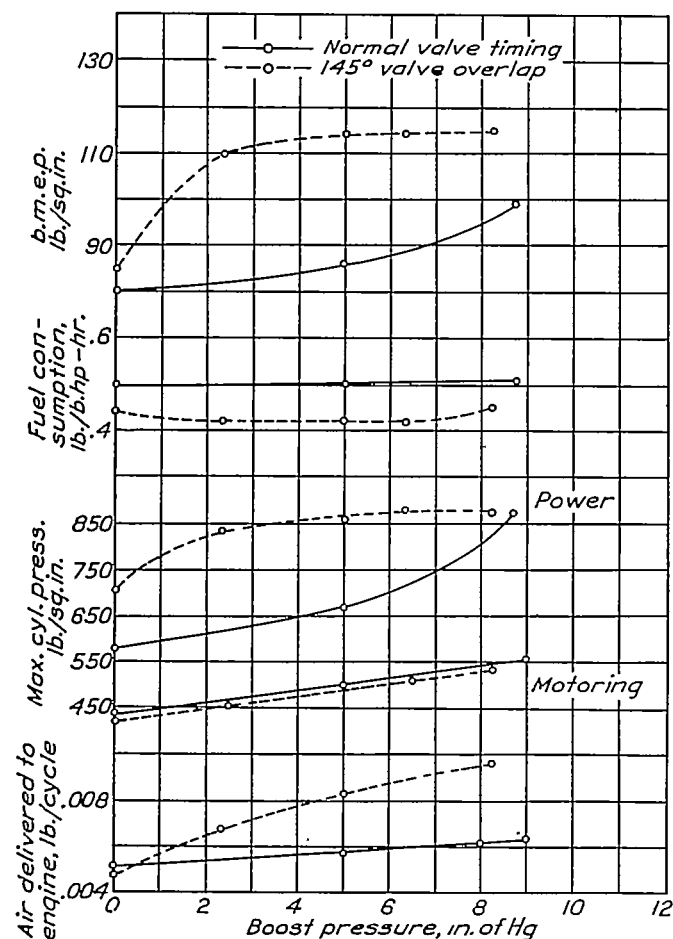


FIGURE 6.—Effect of scavenging on engine performance (clear exhaust, 1,500 r.p.m.).

lower values than for normal operation for all boost pressures, probably as a result of a decrease in the air retained in the cylinder and of a loss of the heat carried by the residual gases.

It should be noted that as the boost pressure is increased the brake mean effective pressure with clear exhaust and normal valve timing approaches that obtained with valve overlap, and at some high boost pressure would probably equal the brake mean effective pressure with valve overlap. This condition is brought about mainly by the improved combustion characteristics caused by the decreasing proportional amount of residual gases. As the boost pressure increases, there is inducted an increasingly greater air charge, and as the weight of residual gases is dependent upon the exhaust back pressure, they remain practically constant and become a proportionally smaller part of the new charge in the cylinder. This decreased effect of the residual gases for a boost condition is probably responsible to a

large degree for the smoother engine operation noted in the previous discussion.

The compression-ignition engine always has a large excess of air available when starting or idling and the use of valve overlap does not require any special arrangements or apparatus for maintaining a proper mixture ratio. In the course of these tests the starting and idling characteristics of the engine were quite satisfactory and no difference could be detected between starting or idling with normal valve timing and with valve overlap. The variation in boost pressure, as could be expected, had no effect on either starting or idling.

Exhaust-gas analysis has shown that with clear exhaust operation and normal valve timing the compression-ignition engine has less than one half of 1 percent carbon monoxide gas in the exhaust. During a test with the large valve overlap and a

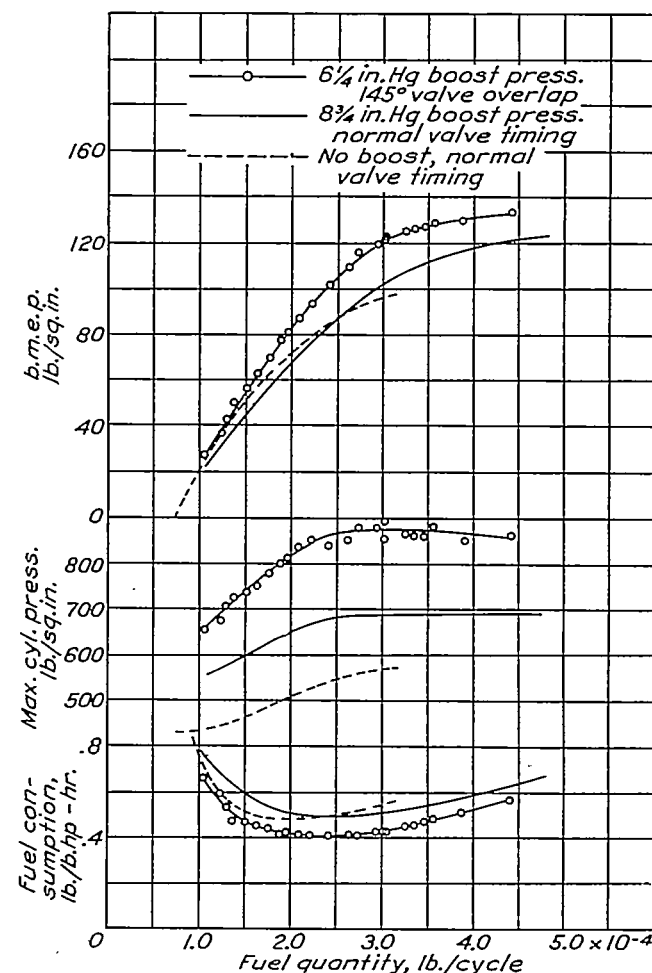


FIGURE 7.—Effect of scavenging on engine performance—variable fuel quantity (1,500 r.p.m., net results).

medium boost pressure enough excess fuel was injected to show excessive smoke and flame in the exhaust, but the exhaust-gas analysis showed only three quarters of 1 percent carbon monoxide gas.

Figure 7 shows the effect of scavenging the combustion chamber by using 145° valve overlap and

6¼ inches of boost pressure for variable fuel quantity. The unboosted performance and the net performance for 8¼ inches of boost pressure obtained with normal valve timing are shown in comparison with the scavenged net performance. It should be noted that the scavenged performance is better than the un-

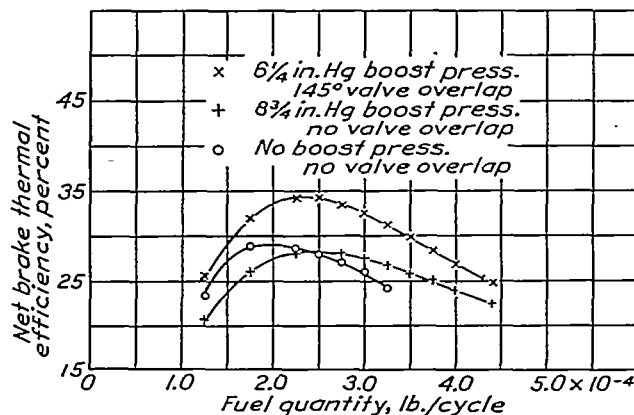


FIGURE 8.—Effect of fuel quantity at different boost pressures on thermal efficiency (speed 1,500 r.p.m.).

scavenged performance for all fuel quantities. Figure 8 shows the net brake thermal efficiencies for these data.

Figure 9 shows the comparative engine performance for variable fuel quantity both for normal valve timing and valve-overlap timing when no boost pressure is used. The increase in engine performance for a scavenged condition is effective over the entire fuel range even though there is less air trapped in the cylinder when using valve overlap as shown by the data for zero boost pressure in figure 8. The increase in the indicated mean effective pressure for all points, including the small fuel quantities where the excess air in the combustion chamber is more than 30 percent, indicates quite definitely that the combustion characteristics are improved when some of the residual gases are removed. The injection advance angle used was 18° for both the normal valve timing and for the valve-overlap data shown on this figure.

Figure 10 shows the effect of speed on engine performance with a boost pressure of 3 inches of mercury, a valve overlap of 145°, and clear exhaust. For each speed the maximum injection advance angle for smooth operation was used, and this limitation made it necessary to retard the advance angle as the speed of the engine was reduced. The fuel quantity was increased to the maximum that would allow clear exhaust for each engine speed and the fuel quantity varied from 0.000256 to 0.000280 pound per cycle. For all practical purposes the fuel quantity could have been held constant and then the brake-horsepower curve would have been practically a straight line. The brake mean effective pressure remained fairly constant over the range of speeds, as did the fuel economy. The brake

thermal efficiency of this engine for the entire speed range was between 29 and 33 percent and the indicated thermal efficiency varied from 33.7 to 40.2 percent.

In figure 11 are shown data taken under conditions simulating propeller load when operating the engine with the large valve overlap and a boost pressure comparable with the pressure from a Roots-type blower driven directly from the engine. The blower used was oversize for the single-cylinder engine and it was only necessary to drive it at one third engine speed. In accordance with the output of a suitably sized and geared blower the boost pressures were increased linearly from 3¼ inches of mercury at an engine speed of 900 r.p.m. to 6¼ inches of mercury at 1,700 r.p.m. When making the propeller-load run, the full-load rating of the engine was arbitrarily taken to be 38 brake horsepower at 1,700 r.p.m. At this rating there was a small amount of smoke and flame present in the exhaust. The exhaust was clear for the speeds less than 1,600 r.p.m., which indicates efficient operation in the cruising range. For a range of speeds

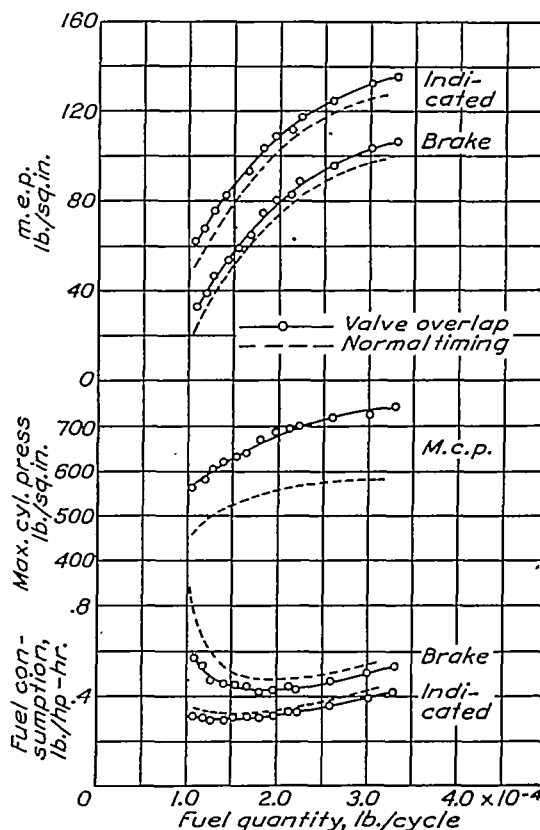


FIGURE 9.—Comparison of engine performance using normal valve timing and 145° valve overlap (no boost, 1,500 r.p.m.).

from 1,600 r.p.m. to 1,100 r.p.m the fuel consumption is between 0.47 and 0.435 pound per brake horsepower per hour. The flatness of the fuel-economy curve for variable speed indicates the desirability of this type of engine operation for aircraft. In order not to exceed an allowable knock, it was necessary to retard the

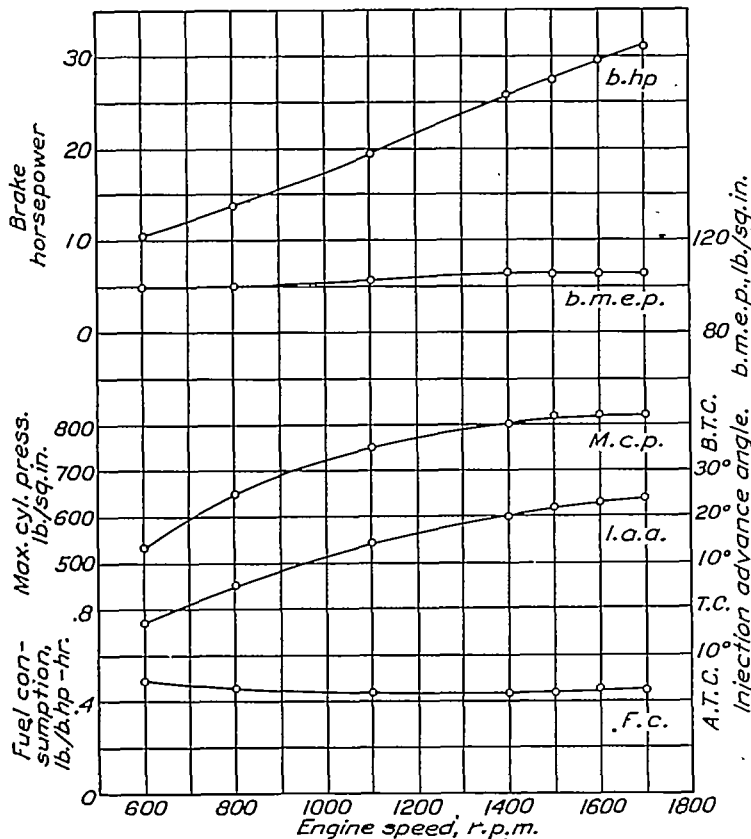


FIGURE 10.—Effect of engine speed on performance with clear exhaust (145° valve overlap, 3 inches Hg boost pressure).

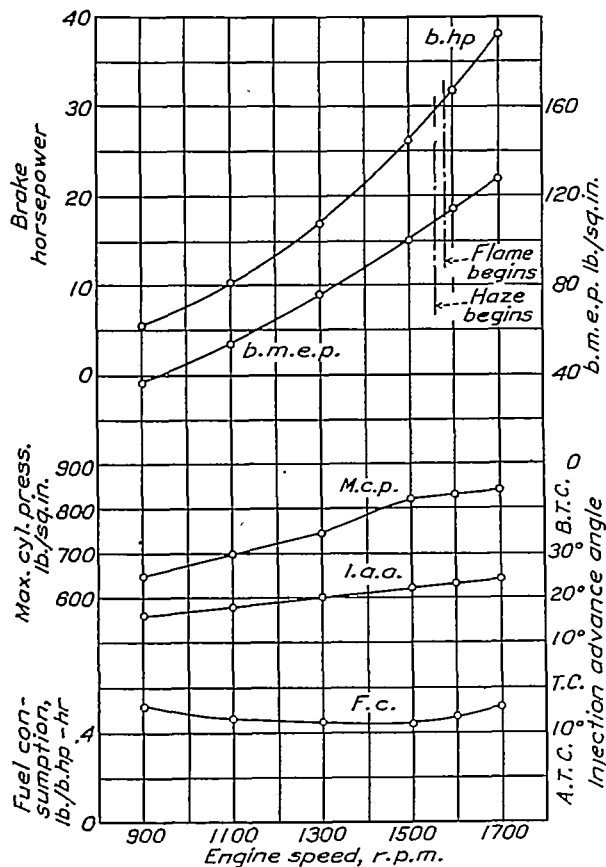


FIGURE 11.—Effect of propeller loading on engine performance (145° valve overlap boost pressure: 3½ inches Hg at 900 r.p.m. to 6½ inches Hg at 1,700 r.p.m.).

injection advance angle for reduced speeds as in the other variable-speed tests, but to a lesser degree, owing to the reduction in fuel quantity for the reduced speeds.

The friction mean effective pressures as affected by speed, boost pressures, and valve overlap are shown in figure 12. The values shown are for the engine alone, as the blower was separately driven. Practically no difference is observable between the friction mean effective pressures for normal valve timing and for the large valve overlap. Boosting the inlet pressure decreases the friction mean effective pressure because the induction air does work on the piston. If the blower were geared directly to the engine shaft, the values shown would of course be increased by the amount of mean effective pressure required to drive the blower. For example, at 1,500 r.p.m. and 8½ inches of mercury boost, the friction mean effective pressure would be 36 pounds per square inch instead of 27.

Figure 13 shows an indicator card taken with the Farnboro indicator while obtaining the data for figure 6. The performance values are 143.5 pounds per square inch indicated mean effective pressure, 111 pounds per square inch net brake mean effective pressure, and a net specific fuel consumption of 0.407 pound per brake horsepower per hour with a clear exhaust. The boost pressure was 6½ inches of mercury and the valve overlap 145°. The

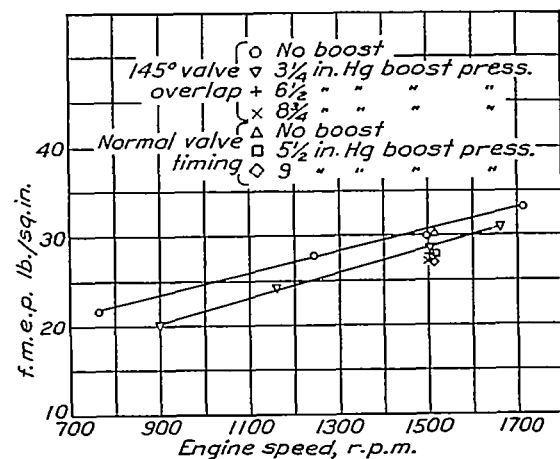


FIGURE 12.—Effect of speed, boost pressure, and valve timing on f.m.e.p.

multiplicity of points on the indicator card shows the large number of engine cycles used for recording this pressure-time diagram and the small dispersion of the points indicates the regularity and consistency with which the pressure cycle repeated itself when the engine was operating with boosting and valve overlap.

It may be noted that for 3 inches of boost pressure and 1,500 r.p.m. the brake mean effective pressure on figure 10 is 106 pounds per square inch; whereas for the same boost pressure and speed, 112 pounds per

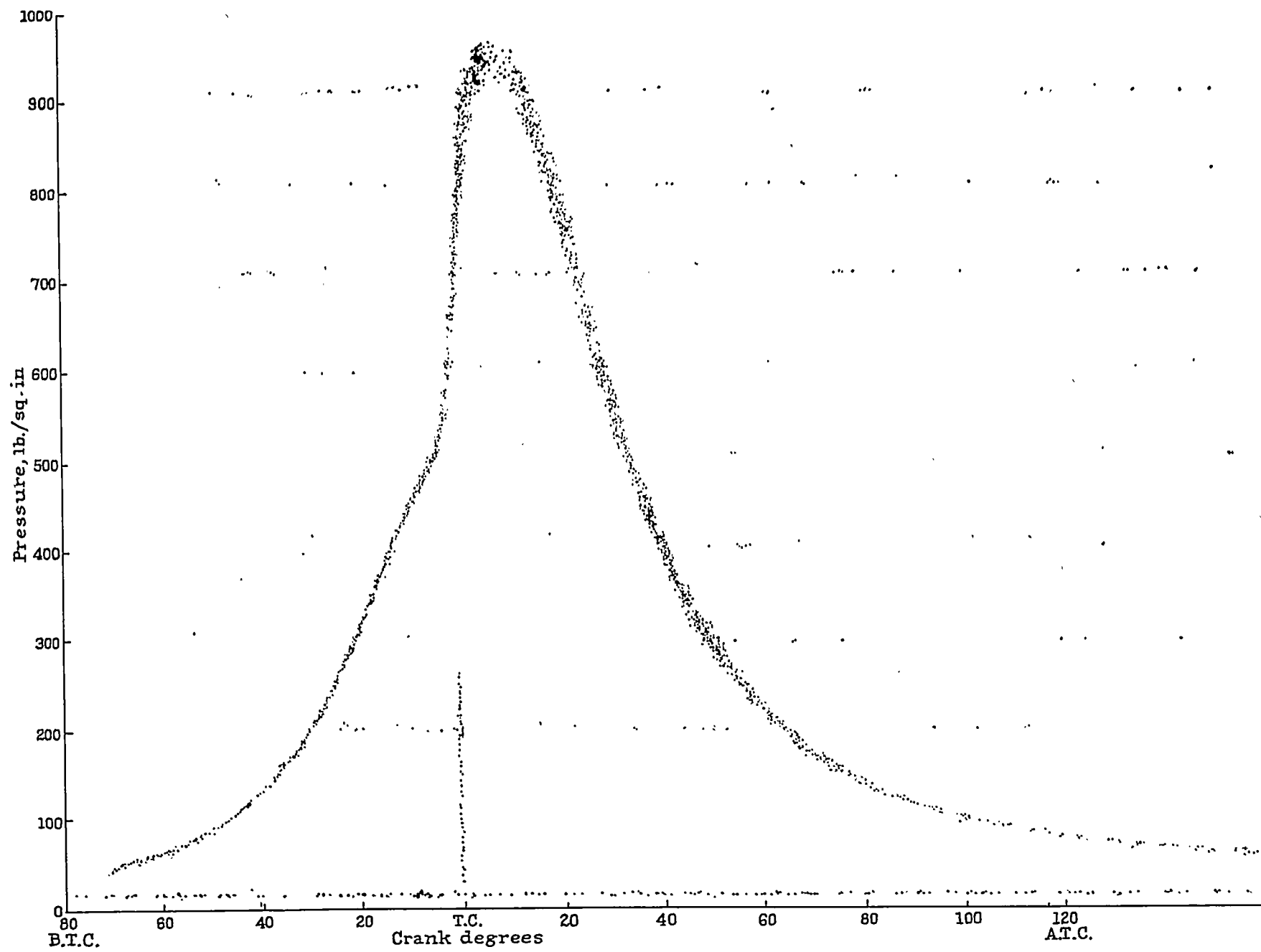


FIGURE 13.—Indicator card taken with Farnbero indicator.

square inch is shown on figure 6. The difference is due principally to the use of two different fuels and the different fuel quantities considered to give clear exhaust. The fuels are noted as no. 1 and no. 2 in reference 5. Fuel no. 1 has a longer ignition lag and therefore a faster rate-of-pressure rise and a greater tendency to knock than fuel no. 2. Observations of engine power and inspection of the exhaust show that both fuels will carry the same load with practically clear exhaust up to flame start, but with fuel no. 2 a haze precedes the start of flame as shown in figure 11. The appearance of this haze may be accounted for by the shorter ignition lag of the fuel and the correspondingly earlier occurrence of high temperatures due to combustion, which would cause some of the fuel from the latter part of the injection to pass through regions of high temperature, and probably cause the formation of free carbon particles. This early occurrence of high temperatures would also tend to reduce the penetration and prevent some fuel from reaching sufficient air for combustion.

Indicator cards taken during the variable-speed tests showed that the rate-of-pressure rise in pounds per degree of crank travel decreased as the engine speed was increased. At 1,700 r.p.m. there was practically no audible knock. Although it was not deemed advisable to operate the single-cylinder test engine at higher speeds, there was nothing in the fuel system or engine combustion characteristics to indicate that speeds higher than 1,700 r.p.m. could not be used to advantage.

In view of the cooling effects that result from scavenging the combustion chamber with fresh air and the improved combustion characteristics resulting from the removal of the residual gases, it was considered advisable to investigate the heat loss to the cooling system under conditions of normal valve timing and for scavenging conditions when using valve overlap. It was found that with normal valve timing the heat loss to the coolant was 17.0 percent of the total heat of the fuel, and by using the large valve overlap and a scavenging pressure of $3\frac{1}{4}$ inches of mercury this heat loss was not materially reduced.

All the test data herein reported were obtained at a compression ratio of 12.6 but, for purposes of determining the optimum available compression ratio, comparative tests were made at a compression ratio of 15.0. It was found that at the high compression ratio it was not practicable to boost with normal valve timing, for the reduction in ignition lag reduced the permissible injection advance angle to a point where good distribution of the fuel throughout the air charge was not possible in the time available, and the exhaust became hazy for reasons previously stated. The use of a large

valve overlap allowed smoother boosted operation at the high compression ratio than the normal valve timing but, with either, the high compression pressures caused the maximum cylinder pressures to be raised from 150 to 200 pounds per square inch higher than at the lower compression ratio, and the resultant engine performance was not as good. For best engine operation the injection advance angle was increased to a point where the indicator card showed the cylinder pressure breaking away from the compression line ahead of top center. For the compression ratio of 15.0 the injection advance angle was necessarily retarded below that used at the lower compression ratio and, for a full-load fuel quantity and with optimum injection advance angle, the maximum cylinder pressure for the compression ratio was 1,000 pounds per square inch.

The better engine performance at the 12.6 compression ratio indicates that a range of compression ratios should be investigated so as to establish the most advantageous balance between the requirements for favorable combustion characteristics and the requirements for proper formation of the necessary mixture of fuel and air.

CONCLUSIONS

Boosting the air charge of a high-speed 4-stroke-cycle compression-ignition engine without removing the residual gases tends to make the engine operation smoother, and for a vertical-disk form of combustion chamber operated at a compression ratio of 12.6 the indicated mean effective pressure is increased in proportion to the additional air inducted.

Removing the residual gases from the clearance volume of a compression-ignition engine improves the combustion characteristics, results in decreased specific fuel consumption, and permits operating at higher fuel quantities with a clear exhaust.

The residual gases can be removed efficiently from the clearance volume of a high-speed, 4-stroke-cycle compression-ignition engine by using a valve overlap of 145° and a pressure difference of from 2 to 5 inches of mercury across the inlet and exhaust ports.

The increase in engine power effected by scavenging the combustion chamber of a compression-ignition engine is greater than the increase that can theoretically be obtained by adding additional air equivalent to the replacement volume of exhaust gases.

The starting and idling characteristics of a compression-ignition engine are not affected either by boosting or by scavenging with a large valve overlap.

The operation of this engine at a compression ratio of 15 at high scavenging pressures was unsatisfactory because of inferior performance and higher maximum cylinder pressures.

The percentage of carbon monoxide gas in the exhaust of a compression-ignition engine when operating with a clear exhaust is less than one half of 1 percent.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *June 10, 1933.*

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